

# **Using Ground-Based Measurements and Retrievals to Validate Satellite Data**

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## **1. Scientific goals**

The proposed research is to use the DOE ARM ground-based measurements and retrievals as the ground-truth references for validating satellite cloud results and retrieving algorithms. This validation effort includes four different ways: (1) cloud properties on different satellites, therefore different sensors, TRMM VIRS and TERRA MODIS; (2) cloud properties at different climatic regions, such as DOE ARM SGP, NSA, and TWP sites; (3) different cloud types, low and high level cloud properties; and (4) day and night retrieving algorithms. Validation of satellite-retrieved cloud properties is very difficult and a long-term effort because of significant spatial and temporal differences between the surface and satellite observing platforms. The ground-based measurements and retrievals, only carefully analyzed and validated, can provide a baseline for estimating errors in the satellite products. Even though the validation effort is so difficult, a significant progress has been made during the proposed study period, and the major accomplishments are summarized in the follow.

## **2. Accomplishment Outline**

- (1) Validated CERES/VIRS cloud products using ARM SGP and TWP data
- (2) Validated CERES-derived MODIS cloud products using ARM SGP data
- (3) Validated GOES cloud products using the surface observations and aircraft in situ measurements during the March 2000 ARM Cloud IOP at SGP site
- (4) Performed the first cloud validation study over Arctic area using surface, satellite and aircraft during FIRE ACE
- (5) Validated CERES-derived MODIS cloud products using DOE NSA data
- (6) Derived Arctic stratus cloud properties and radiative forcing at the ARM NSA site
- (7) Developed a solar-independent retrieval algorithm for ARM radar-related retrievals
- (8) Presented the cloud-validation-related studies at 7 CERES STMs and 5 other professional meetings
- (9) Published 7 referred papers and 2 NASA validation documents, and one paper in preparation.

### 3. Accomplishments and Summary of Research

#### 3.1 Validated CERES/VIRS cloud products using ARM SGP and TWP data

Cloud macrophysical and microphysical properties derived from the Tropical Rainfall Measurement Mission (TRMM) Visible Infrared Scanner (VIRS) as part of the Clouds and the Earth's Radiant Energy System (CERES) project during January-December 1998 are compared to simultaneous ground-based observations. The ground-based data taken over the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains (SGP) site are used as “ground truth” data set in the validation of the CERES cloud products and to improve the CERES daytime and nighttime cloud retrieval algorithms. The CERES cloud products include effective cloud height and temperature, cloud-droplet effective radius, optical depth, and LWP/IWP. The CERES cloud products were averaged in a 30-km x 30-km spatial resolution centered on the ARM SGP site, while the surface data were averaged over an hour centered at the time of the TRMM overpass. A total of 59 daytime and 80 nighttime cloudy samples were available for the first 12 months of CERES observations. Only those radar scenes that are classified almost entirely as either single layer cirrus or low-level stratus clouds are used in the comparison of cloud microphysical properties. For stratus comparisons, 25 and 22 samples were available for daytime and nighttime, respectively, compared to 10 and 25 cirrus samples. Overall, the VIRS-derived daytime cloud macrophysical and microphysical properties are in excellent agreement with the surface results despite large differences in temporal and spatial sampling between the two datasets, indicating that the VIRS daytime cloud results are accurate and reliable (Figure 1). The nighttime cloud macrophysical and microphysical properties from VIRS do not compare with the surface data as well as the daytime results because of the limited range of information that can be derived from infrared data emitted optically thick clouds.

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- Dong, X.**, P. Minnis, G.G. Mace, S.Sun-Mack, E.E. Clothiaux, and J.C. Liljegren, 2002: Validation of VIRS cloud property retrievals using ground-based measurements obtained at the DOE ARM SGP site. In preparation for *J. Atmos. Sci.*
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### Daytime stratus clouds at the ARM SGP Site

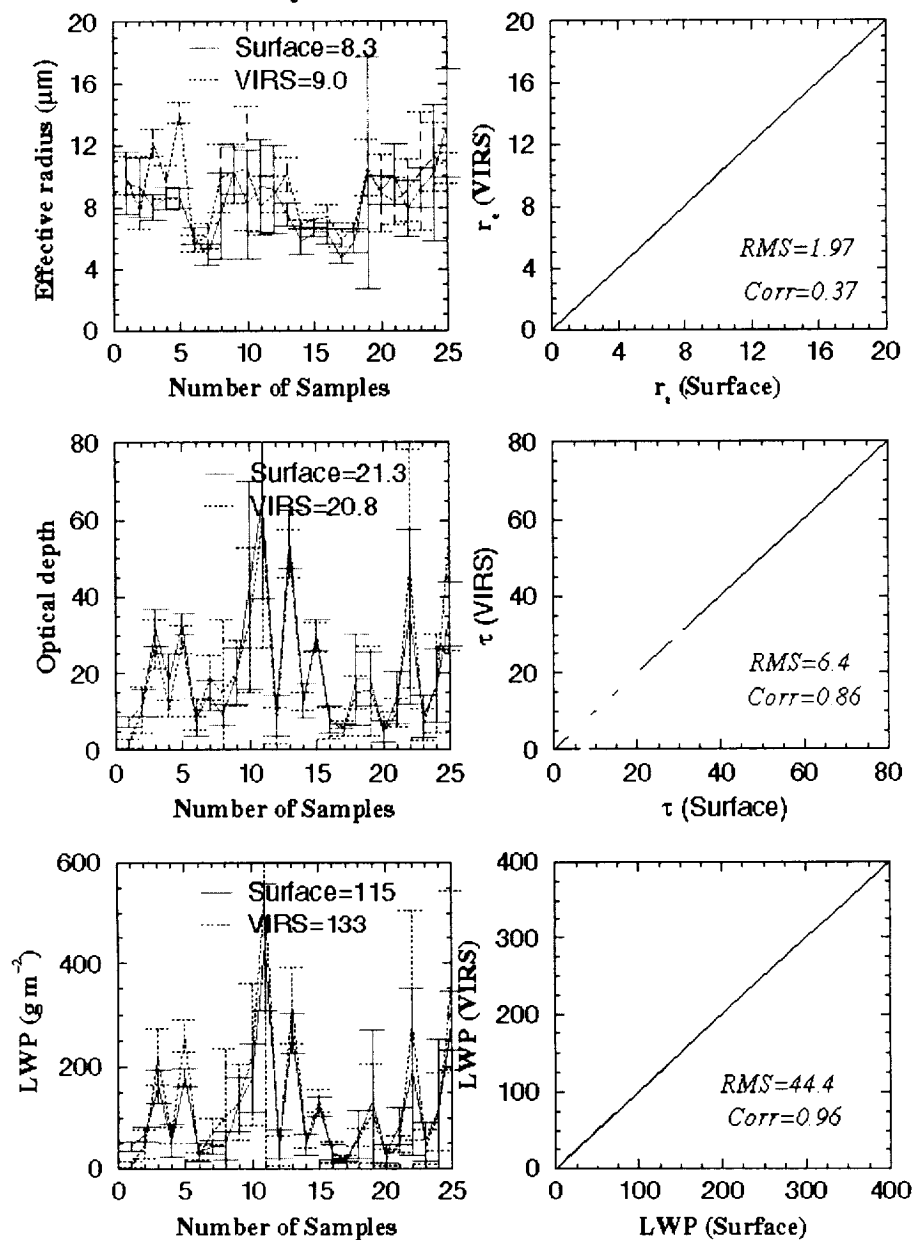


Figure 1. Comparison of daytime stratus cloud microphysical properties over the ARM SGP site derived from simultaneous VIRS and ground-based instrument data during January-December 1998. The VIRS means and standard deviations were derived from all pixels within a 30-km x 30 km box centered on the surface site, while the surface values were based on the data taken during an hour period centered on the satellite overpass time.

### 3.2 Validated CERES-derived MODIS cloud products using ARM SGP data

Cloud macrophysical and microphysical properties derived from the NASA TERRA (EOS-AM) Moderate Resolution Spectroradiometer (MODIS) as part of the CERES project during November 2000 to June 2001 are compared to simultaneous ground-based observations. The ground-based data taken by the ARM Program are used as “ground truth” data set in the validation of the CERES-derived MODIS cloud products and to improve the MODIS daytime and nighttime cloud retrieval algorithms. The datasets taken over the SGP site were used for this study. The CERES-derived MODIS cloud products include effective cloud height and temperature, cloud-droplet effective radius, optical depth, and LWP/IWP. The MODIS cloud products were averaged in a 30-km x 30-km spatial resolution centered on the ARM SGP site, while the surface data were averaged over an hour centered at the time of the TERRA overpass. There are totally 57 cloudy samples for daytime and 65 cloudy samples for nighttime in this study. Only those radar scenes that are classified almost entirely as either single layer cirrus or low-level stratus clouds are used in the comparison of cloud microphysical properties. The preliminary study shows that the daytime MODIS-derived effective cloud height and temperature, and microphysical properties agree fairly well with surface measurements and retrievals (Figure 2), while the nighttime MODIS-derived effective cloud height is overestimated (Figure 3), and the cirrus cloud microphysical properties, such as  $r_e$ , IWP, and  $\tau$ , are larger than those of surface measurements and retrievals.

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- Dong, X.**, P. Minnis, and S. Sun-Mack, 2002: Comparison of cloud properties retrieved from MODIS, VIRS, and surface data at the ARM SGP site. The 27<sup>th</sup> CERES STM, Princeton University, NJ, Sept. 16-19.
- Dong, X.**, 2002: Ground-based remote sensing: DOE ARM program and its application for validating satellite and model results. International remote sensing and modeling workshop, Beijing, China, Aug. 19-23.
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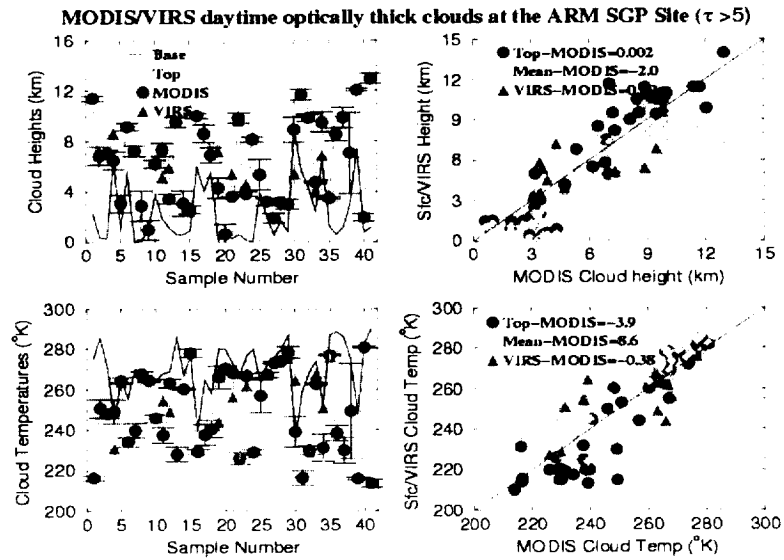


Figure 2. CERES-derived MODIS and VIRS effective cloud temperatures and heights under optically thick ( $\tau > 5$ ) and daytime conditions.

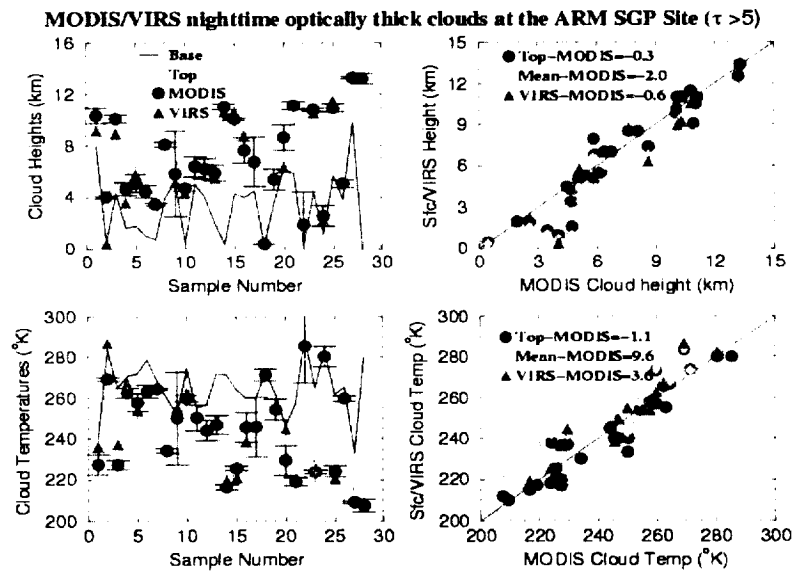


Figure 3. Same as Figure 2, but for nighttime.

### **3.3 Comparison of stratus cloud properties deduced from surface, GOES, and aircraft data during the March 2000 ARM Cloud IOP**

Low-level stratus cloud microphysical properties derived from surface and GOES data during the March 2000 cloud IOP at the ARM SGP site are compared with aircraft in situ measurements. For the surface retrievals, the cloud-droplet effective radius and optical depth are retrieved from a 82-stream radiative transfer model with the input of ground-based measurements, and cloud liquid water path (LWP) is retrieved from ground-based microwave radiometer measured brightness temperature. The satellite results, retrieved from GOES visible, solar-infrared, and infrared radiances, are averaged in a  $0.5^\circ \times 0.5^\circ$  box centered on the ARM SGP site. The FSSP on the University of North Dakota Citation aircraft provided in situ measurements of the cloud microphysical properties. During the IOP, four low-level stratus cases were intensively observed by the ground- and satellite-based remote sensors and aircraft in situ instruments resulting in a total of 10 hours of simultaneous data from the three platforms. In spite of the large differences in temporal and spatial resolution between surface, GOES, and aircraft, the surface retrievals have excellent agreement with the aircraft data overall for the entire 10-hour period, and the GOES results agree reasonably well with the surface and aircraft data and have similar trends and magnitudes except for the GOES-derived effective radii, which are typically larger than the surface- and aircraft-derived values. The means and standard deviations of the differences between the surface and aircraft effective radius, LWP, and optical depth are  $-4 \pm 20.1\%$ ,  $-1 \pm 31.2\%$ , and  $8 \pm 29.3\%$ , respectively, while their correlation coefficients are 0.78, 0.92, and 0.89, respectively during the 10-hour period (Figure 4). The differences and correlations between the GOES-8 and aircraft results are of a similar magnitude, except for the droplet sizes. The averaged GOES-derived effective radius is 23% or  $1.8 \mu\text{m}$  greater than the corresponding aircraft values, resulting in a much smaller correlation coefficient of 0.18. Additional surface-satellite datasets were analyzed for time periods when the aircraft was unavailable. When these additional results are combined with the retrievals from the four in situ cases, the means and standard deviations of the differences between the satellite-derived cloud-droplet effective radius, LWP, and optical depth and their surface-based counterparts are  $16 \pm 31.2\%$ ,  $4 \pm 31.6\%$ , and  $-6 \pm 39.9\%$ , respectively. The corresponding correlation coefficients are 0.24, 0.88, and 0.73. The frequency distributions of the two datasets are very similar indicating that the satellite

retrieval method should be able to produce reliable statistics of boundary-layer cloud properties for use in climate and cloud process models.

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- Dong, X.,** P. Minnis, G.G. Mace, W.L. Smith Jr, M. Poellot, R. Marchand, and A. Rapp, 2002: Comparison of stratus cloud properties deduced from surface, GOES, and aircraft data during the March 2000 ARM Cloud IOP. *J. Atmos. Sci.*, **59**, 3265-3284.
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### Comparison of Surface, GOES and Aircraft Results (~10 hours)

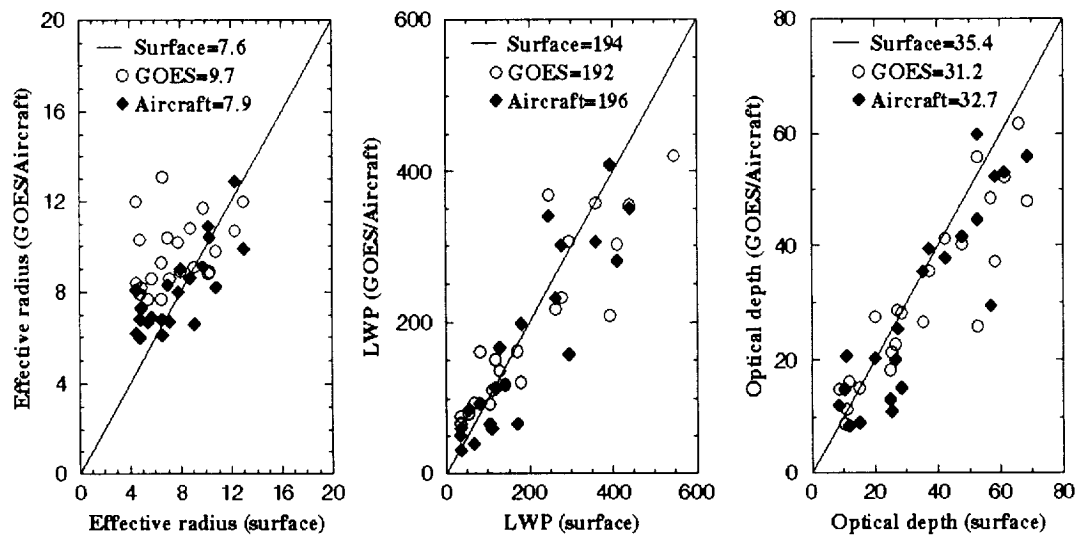


Figure 4. The results of surface, GOES, and aircraft datasets from the four in situ cases during the 10-hour period (30-min resolution) at the ARM SGP site.



### **3.4 Performed the first cloud validation study over Arctic area using surface, satellite, and aircraft during FIRE ACE**

To study Arctic stratus cloud properties and their effect on the surface radiation balance during the spring transition season, analyses are performed using data taken during 3 cloud and 2 clear days in May 1998 as part of the First ISCCP Regional Experiment (FIRE) Arctic Cloud Experiment (ACE). Radiative transfer models are used in conjunction with surface- and satellite-based measurements to retrieve the layer-averaged microphysical and shortwave radiative properties. The surface-retrieved cloud properties in Cases 1 and 2 agree well with the in situ and satellite retrievals. Discrepancies in Case 3 are due to spatial mismatches between the aircraft and surface measurements in a highly variable cloud field. Also, the vertical structure in the cloud layer is not fully characterized by the aircraft measurements. Satellite data are critical for understanding some of the observed discrepancies. The satellite-derived particle sizes agree well with the coincident surface retrievals and with the aircraft data when they were collocated. Optical depths derived from visible-channel data over snow backgrounds were overestimated in all three cases suggesting that methods currently used in satellite cloud climatologies derive optical depths that are too large. Use of a near-infrared channel with a solar infrared channel to simultaneously derive optical depth and particle size appears to alleviate this overestimation problem. Further study of the optical depth retrieval is needed. The surface-based radiometer data reveal that the Arctic stratus clouds produce a net warming of  $20 \text{ Wm}^{-2}$  in the surface layer during the transition season suggesting that these clouds may accelerate the springtime melting of the ice pack. This surface warming contrasts with the net cooling at the top of atmosphere (TOA) during the same period.

#### **Reference**

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### 3.5 Validated CERES-derived MODIS cloud products using DOE NSA data

Three cases, March 22, 30, and 31 2001, have been selected to compare the MODIS-derived effective heights with surface-based radar and lidar measured cloud top and base heights over the ARM NSA site. There were totally 14 overpasses during the 3-day period, and 7 MODIS-derived effective heights were within surface-based lidar and radar measured cloud base and top heights, 5 were overestimated, and 2 were underestimated. While the comparison of cloud microphysics from 00 and 02 UT, March 22, 2001, suggests that more studies are needed for validating MODIS cloud products over the Arctic region, and the first step is to focus on summer season.

Table 1 MODIS Cloud Properties over the ARM NSA site (3/22/01)

Time (UT)	00	02	20	22	24
$r_e$ ( $\mu\text{m}$ )	8.2 / 5.0 (modis/sfc)	8.9 / 5.0 (modis/sfc)	48.5	51.4	32.3
LWP ( $\text{gm}^{-2}$ )	358 / 35 (modis/sfc)	43 / 25 (modis/sfc)	284	48.2	547
$\tau$	62 / 10 (modis/sfc)	7.8 / 7.5 (modis/sfc)	90	1.4	32.1

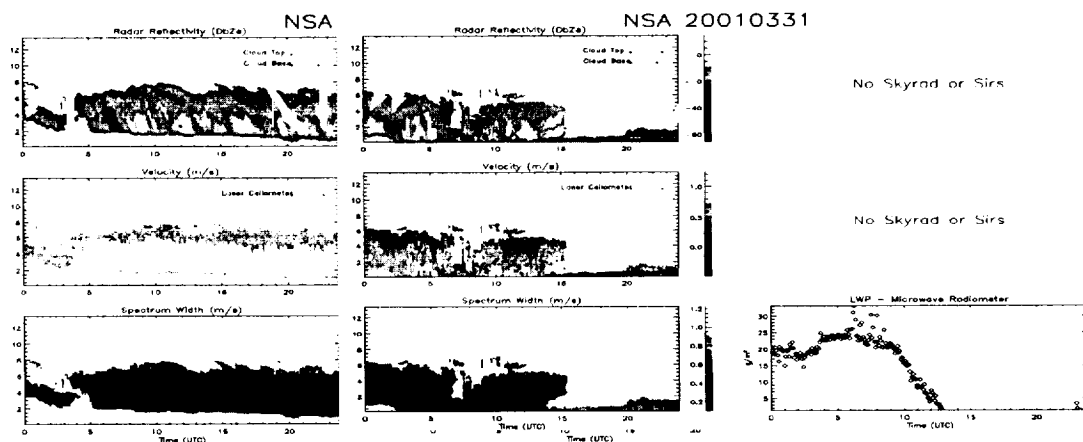


Figure 5. Comparison of satellite-derived effective cloud heights (arrows) with surface-based radar measurements over the ARM NSA site on March 30 and 31 2001.

### Reference

**Dong, X.,** P. Minnis, and S. Sun-Mack: Validation effort for Langley-derived MODIS cloud results at ARM NSA site: case study. The 26<sup>th</sup> CERES STM, Williamsburg, VA, May 14-16.

### **3.6 Derived Arctic stratus cloud properties and radiative forcing at ARM NSA site**

A record of single-layer and overcast low-level Arctic stratus cloud properties has been generated using data collected from May to September 2000 at the ARM NSA site near Barrow, Alaska. The record includes liquid-phase and liquid dominant mixed-phase Arctic stratus macrophysical, microphysical, and radiative properties, as well as surface radiation budget and cloud radiative forcing. The macrophysical properties consist of cloud fractions, cloud base/top heights and temperatures, and cloud thickness derived from a ground-based radar and lidar pair, and rawinsonde sounding. The microphysical properties include cloud liquid water path and content, and cloud-droplet effective radius and number concentration obtained from microwave radiometer brightness temperature measurements, and the new parameterization. The radiative properties contain cloud optical depth, effective solar transmission, and surface/cloud/top-of-atmosphere albedos derived from the new parameterization and standard Epply precision spectral pyranometers. The shortwave, longwave, and net cloud radiative forcings at the surface are inferred from measurements by standard Epply precision spectral pyranometers and pyrgeometers. There are approximately 300 hours and more than 3600 samples (5-min resolution) of single-layer and overcast low-level stratus during the study period. The 10-day averaged total and low-level cloud ( $Z_{top} < 3$  km) fractions are 0.87 and 0.55, and low-level cloud base and top heights are around 0.4 km and 0.8 km. The cloud-droplet effective radii and number concentrations in the spring are similar to midlatitude continental stratus cloud microphysical properties, and in the summer they are similar to midlatitude marine stratus clouds. The total cloud fractions in this study show good agreement with the satellite and surface results compiled from data collected during the FIRE ACE) and the SHEBA field experiments in 1998. The cloud microphysics derived from this study, in general, are similar to those collected in past field programs although these comparisons are based on data collected at different locations and years. At the ARM NSA site, the summer cooling period is much longer (2-3 months vs. 1-2 weeks), and the summer cooling magnitude is much larger ( $-100 \text{ W m}^{-2}$  vs.  $-5 \text{ W m}^{-2}$ ) than at the SHEBA ship under the conditions of all skies at the SHEBA and overcast low-level stratus clouds at the NSA site.

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### **3.7 An integrated algorithm for retrieving low-level stratus cloud microphysical properties using millimeter radar and microwave radiometer data**

The microwave radiometer-derived cloud liquid water path ( $lwp$ ) and a profile of radar reflectivity are used to derive a profile of cloud liquid water content ( $lwc$ ). Two methods ( $M1$  and  $M2$ ) have been developed for inferring the profile of cloud-droplet effective radius ( $r_e$ ) in liquid phase or liquid dominant mixed phase stratocumulus clouds. The  $M1$ -inferred  $r_e$  profile is proportional to a previously derived layer-mean  $r_e$  and to the ratio of the radar reflectivity to the integrated radar reflectivity. This algorithm is independent of the radar calibration and is applicable to overcast low-level stratus clouds that occur during the day because it is dependent on solar transmission observations. In order to extend the retrieval algorithm to a wider range of conditions, we describe a second method that uses an empirical relationship between effective radius and radar reflectivity based on theory and the results of  $M1$ . Sensitivity studies show that the surface-retrieved  $r_e$  is more sensitive to the variation of radar reflectivity when the radar reflectivity is large, and the uncertainties of retrieved  $r_e$  related to the assumed vertically constant cloud-droplet number concentration and shape of the size distribution are about 9% and 2%, respectively. For validation, a total of 10 hours of aircraft data and 36 hours of surface data were collected over the ARM SGP site during the March 2000 cloud IOP. More detailed comparisons in two cases quantify the agreement between the aircraft data and the surface retrievals. When the temporal averages of the two datasets increase from 1-min to 30-min, the means and standard deviations of differences between the two datasets decrease from  $-2.5\% \pm 84\%$  to  $1.3\% \pm 42.6\%$  and their corresponding correlation coefficients increase from 0.47 to 0.8 for  $lwc$ ; and decrease from  $-4.8\% \pm 36.4\%$  to  $-3.3\% \pm 22.5\%$  with an increased coefficients from 0.64 to 0.94 for  $r_e$  (both  $M1$  and  $M2$ ). The agreement between the aircraft and surface data in the 30-min averages suggests that the two platforms are capable of characterizing the cloud microphysics over this temporal scale. On average, the surface retrievals are unbiased relative to the aircraft in situ measurements. However, when we select only the 1-min averaged aircraft data within 3 km of the surface

site, the means and standard deviations of differences between the two datasets are larger ( $23.4\% \pm 113\%$  for  $lwc$  and  $28.3\% \pm 60.7\%$  for  $r_e$ ) and their correlation coefficients are smaller (0.32 for  $lwc$  and 0.3 for  $r_e$ ) than those from all 1-min samples. This result suggests that restricting the comparison to the samples better matched in space and time between the surface and aircraft data does not result in a better comparison.

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- Dong, X.**, and G.G. Mace, 2003: Profiles of low-level stratus cloud microphysics deduced from ground-based measurements. *J. Atmos. and Oceanic Tech.* In press.
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- 3.8 Attended 7 NASA CERES STMs and 5 other professional meetings**
- Dong, X.**, P. Minnis, and S. Sun-Mack, 2002: Comparison of cloud properties retrieved from MODIS, VIRS, and surface data at the ARM SGP site. The 27<sup>th</sup> CERES STM, Princeton University, NJ, Sept. 16-19, 2002.
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### **3.9 Current grant referred publications**

- Dong, X.**, P. Minnis, G.G. Mace, S. Sun-Mack, E.E. Clothiaux, and J.C. Liljegren, 2002: Validation of VIRS cloud property retrievals using ground-based measurements obtained at the DOE ARM SGP site. In preparation for *J. Atmos. Sci.*
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